Journal of Applied Sciences

ISSN 1812-5654

science alert

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Journal of Applied Sciences 11 (4): 671-678, 2011
ISSN 1812-5654 / DOI: 10.3923/jas.2011.671.678

A Multi-objective Model for Selecting Treatment Facilities in a Regional Special Waste Management Plan

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Abstract: In this study, a multi-objective model for selecting special waste treatment facilities in a regional geographic contest is presented. The evolution of knowledge, needs, technologies and available founds makes possible to consider a Regional Special Waste Management Plan not just as a deliberative act, but like a dynamic process for which it is necessary to individualize, step by step, strategic solutions with the support of adequate evaluation techniques, conforming with the notion of environmental and financial sustainability. In case of multi-objective problems, like waste treatment is, the use of multi criteria analysis for generation, evaluation and selection of different planning scenarios, seems to be appropriate. This approach allows transforming a decisional multi-objective problem in a mono-objective constrained optimization problem.

Key words: Costs-benefits analysis, project selection, constrained optimization, regional special waste management plan

INTRODUCTION

According to current Italian legislation[1], special waste management is a public interest activity.

Given the existing trade-off between economic and environmental objectives, that generally concerns this activity, it is considered a complex and remarkable problem for all societies. Decision-makers have to consider priorities and factors that imply to choose between a wide range of proposals, evaluating impacts associated with different variables, in order to find a best compromise solution (Rostirolla, 1998).

The aim of this work is to illustrate a decision support system application, based on a multi-objective method for treatment plants selection in a Regional Special Waste Management Plan. Local power and strong rights of *veto* normally affect the plan, which prevent to realize an integration of different aspects, jointly.

The complexity of a coordinated and integrated management of special waste is related to waste characteristics, technological components and political-administrative factors. These elements are present during all waste life cycle and their management is complicated by the separation of competences between public subjects and market (Massarutto, 2007).

On the basis of special waste European classification (Dir. 75/442), special waste categories are divided in 20 macro-areas, related to manufacturing sector that origin them. The variety of special wastes requires the need to choose not only between different treatment technical solutions, but also to select the best measures and administrative instruments, in order to obtain a strategic management, targeted to reduce pollution risks, waste amount and waste noxiousness. These are the main objectives pursued by the European special waste policy (European Commission, 2000). This policy, based on recycling and using waste as energy resource, is founded on the “polluter-pays” principle[2] and [Art. 174, Amsterdam Treaty (1997)] on the “Waste Management Hierarchy[3]” (Com 205/666, p. 4), consisting, first of all, in to avoid waste production (prevention) and secondly, to concentrate the attention on waste recovery and recycling (European Commission, 2005).

On this point, as the European legislation recommends, planning is the first step to develop proper management. Generally, a Regional Special Waste Management Plan consists in the exposition of: type and

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[1] D.lgs 152/06 and D.lgs. 4/08

[2] Art. 174 , Amsterdam Treaty (1997)

[3] COM 205/666, p. 4

amount of recyclable and recoverable waste; technical requirements; hazardous waste special provisions; estimated costs of several activities, like collection, pre-treatment, heat/physicochemical treatment, post-treatment and final disposal in landfill (European Commission, 2003).

Considering the local jurisdiction, the Plan shows general goals and establishes the best solution about location, types of disposal plants and useful technologies (L. R. n 4, 28/03/2007).

With the intention of decide which installations are the most eligible, given a geographical context and considering exogenous constraints (availability of public founds-that are generally limited-emission retention, social acceptance, transport networks, etc.) and constraints between variables, economic analysis could be helpful (Fiorucci *et al.*, 2003; Shmeleva and Powell, 2006). It could be aimed to different objectives: to define the best compromise solution among socially relevant objectives pursued by local authorities; to quantify investment costs; to realize or to adapt treatment plants; to quantify operative incomes and costs, in order to consider the existent legislative framework and the incentive arrangements; to check the financial sustainability as an indicator to establish if, for the private sector, waste management is cost-effective. In the last case it could be suitable to favour a competition for the market. The economic evaluation has to be made before taking definitive decisions about the plan.

APPLICATION OF MULTI-OBJECTIVE MATHEMATICAL PROGRAMMING TECHNIQUES FOR COMPLEX PROBLEMS

Decision-making process in the field of waste is a complex problem that seems to offer a wide range of possibilities to apply mathematical programming techniques, with the goal of finding an optimal solution (Minciardi *et al.*, 2008). The aim is not to find an "optimum", but to support decision-makers in defining an integrated and strategic waste management, depending on the notion of environmental, economic and social sustainability.

Considering several aspects and objectives involved, multi criteria evaluation approach allows overcoming limits of techniques, like social cost-benefit analysis[4].

This method is functional in evaluation of a single project. Otherwise it could be helpful to turn to an alternative decisional support system to analyse, jointly, aggregation, evaluation and scoring steps of actions to be carried out.

The method suggested, based on mathematical programming techniques with binary variables, transforms the multi-dimensional and multi-objective decision problem in a mono-objective constrained optimization ones[5]. This technique leads to maximize or minimize a specific objective, taking into account the achievement of exogenous targets. The results are Pareto optimal solutions: this implies that the last solution is not necessarily the best one, but the most desired in accordance with decision-makers preferences.

The process is structured in several phases that consist in:

- Goal-plan definition
- Indicator definition
- Demand quantification
- Operative alternative definition
- Identification of relations between alternatives (exclusion, dependence, complementarity)
- Kmpact quantification, associated to each alternatives
- Multi-objective mathematical programming model formulation, with binary variables
- Definition of scenarios in terms of values proceeded from exogenous constrains (resources, emission and social acceptance)
- Calculation of the best compromise solution for each scenario
- Identification of "robust" components
- The procedure leads to define a management model and to catch all useful information to formulate an invitation to tender, with the aim of involving private sector

THE DECISIONAL PROBLEM FORMULATION

To set out a decisional support methodology, this work considers a hypothetical decisional problem, aimed to choose which of 28 treatments plants of different categories of special waste, are more eligible to realize an integrated platform, so that to minimize the waste handling and to obtain sufficient economy of scale.

Platform localization has been taken for granted, but the model proposed could be applied to a theoretical case study in the Campania Region, where a Regional Special Waste Management Plan has not yet been adopted.

Plants are differentiated by type of waste or combination of wastes that have to be treated, by technology and size.

Each plant is described as follows[6]:

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[4] About Cost-Benefit Analysis see Rostirolla (1998)

[5] See also: Alcada-Almeida et al. (2009); Chang et al (1997); Chang and Wang (1997); Giannikos (1998)

[6] Data are based on existing treatment facilities business plan and our elaborations

General characteristics: daily and yearly treatment capacity; production of heat and electric energy, according to the calorific values; yearly produced air emission tonnes; amount of marketable materials produced.

Costs: investment costs (acquirement of the area, arrangement of the site, installation of infrastructural, electromagnetic and civil works, starting costs for replacement, etc.); operating costs (labour costs, intermediate services and goods costs, ordinary and extraordinary maintenance costs, materials).

Revenues: there are revenues deriving from the selling of electric energy and heat produced; from the selling of other materials and from the remuneration deriving from special waste disposal;

Profitability index: Net present value and internal rate of return.

Regarding technological aspects (Ansari, 2011; Guner and Yuce, 2005), within a special waste management system, several treatment facilities can generally be found, but we consider:

- Treatment plants with plasma technology (medium and big size: 12 alternatives)
- treatment plants with plasma technology (small size: 13 alternatives)
- Incinerators with energy recovery (2 alternatives)
- Composting plant, so that to transform the organic part of waste in a fertilizer

In the model small size treatment plants corresponds to 50 T/d, medium size corresponds to 100 T/d and the big one treats 200 T/d.

According to ENEA (2008), that shows the advantages of new technology in the field of treatment facilities, we have chosen to take into account non conventional treatment plants, like those using plasma technology: these kinds of heat treatment plants offer strong capacity in energy recovery and they are recommendable to minimize environmental impact associated with special waste. Moreover, by using plasma technology, it is possible to achieve a financial sustainability also when the size of the plant is small, so it generates a great integration with local contexts.

The size of the plants is defined to satisfy the requirement of special waste demands. We suppose that each plant treats about 95% of waste received, producing energy or other marketable products; the remaining part is sent to sanitary landfill.

THE OPTIMIZATION MODEL[7]

In a multi-objective linear programming problem decision variables, impacts and constraints have to be determined.

Treatment plants $(A_1,\dots A_n)$ represent the decision variables associated with a binary variable of existence $(X_{1,\dots}X_n)$, that indicate the presence/absence of them in the final configuration of the special waste management system.

For each potential treatment plants, impacts and objective functions have been considered (Table 1): the coefficients "I" express the impact generated by each option on several objectives. Impacts could be financial, environmental and social ones and they could be expressed by different unit of measures. The objective function indicates if the evaluation criterion has to be minimized or maximized.

According to the use of "What's best" programme, each coefficient has to be multiplied for the variable of existence that could assume value zero (absence) and value 1 (presence) ($Y_1,\dots,Y_n$ and $Z_1,\dots Z_n$ in Table 2): in this way the programme, once it has been chosen a specific objective to be maximize or minimize, considering other objectives such as targets exogenously defined, it will show just the value of the alternatives that will assume value 1 (presence). This means that if the variable of existence linked to that alternative will assume value 1, that alternative (treatment plant) could be included in the platform.

The first step consists in calculating an "ideal vector", constituted by the "optimum" value of each objectives or evaluation criterion (F_1^* and F_2^*). The optimum value is obtained by optimizing individually a specific objective function without any constraint on the other objectives achievement level. The "ideal vector",obviously, is not achievable, but it is a reference to estimate how far the compromised solution is from it (Table 5).

It is possible to consider constraints between variables, indicating, for instance, relations of exclusion or

Table 1: Input matrix

Evaluation criterion	A_1	A_2	A_3	A_n	O.F.
C_1	I_{11}	I_{12}	I_{13}	I_{1n}	Min
C_2	I_{21}	I_{22}	I_{23}	I_{2n}	Max
C_3	I_{31}	I_{32}	I_{33}	I_{3n}	Max
C_n	I_{n1}	I_{n2}	I_{n3}	I_{nn}	Max

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[7] This work uses "What's best" software, produced by Lindo System. See Rostirolla and Monacciani (2008)

Table 2: Structure by which achieve optimal value for ideal vector

Options	A_1	A_2	A_3	A_n			
Variable of existence	$X_{1(0;1)}$	$X_{2(0;1)}$	$X_{3(0;1)}$	$X_{4(0;1)}$			
O.F.:							Optimal value
Min C_1	$y_1=(I_{11}\bullet X)$	$Y_2=(I_{12}\bullet X_j)$	$Y_3=(I_{13}\bullet X_j)$	$Y_n=(I_{1n}\bullet X_j)$			$F_1^* = \text{Min}\sum_1^n y$
Max C2	$Z1=(I_{21}\bullet Xj)$	$Z_2=(I_{22}\bullet X_j)$	$Z_3=(I_{23}\bullet X_j)$	$Z_n=(I_{2n}\bullet X_j)$			$F_2^* = \text{Max}\sum_1^n z$
… …	…	…	…	…			
Max Cn	…	…	…	…			…
Impact Constraints					Total	Sign	Target
C_j	$j_1=(I_{11}\bullet X_j)$	$j_2=(I_{12}\bullet X_j)$	$j_3=(I_{13}\bullet X_j)$	$j_n=(I_{1n}\bullet X_j)$	$\sum_1^n j$	≥	T
…	…	…	…	…	…	…	…
Between variables							
$A_1+A_2+A_3+A_n$	$X_{1(0:1)}$	$X_{2(0:1)}$	$X_{3(0:1)}$	$X_{4(0:1)}$	Σ	≥	1

Table 3: The optimization model

Options	A_1	…	A_n						
Variable	$X_{1(0:1)}$	…	$X_{n(0:1)}$						
O.F.:									Optimal value
Max C_2	$Z_1=(I_{21}\bullet X_j)$``	…	$Z_n=(I_{2n}\bullet X_j)$						$F_2^* = \text{Max}\sum_1^n z$
Impact constrains				Total	Sign	Target	Deviation from ideal vector	Ideal vector	Compromised solution
C_1	Y_1	…	Y_n	$F_1 = \sum_1^n y$	≤	n	$W_1=(F^*_1-F_1)/F^*_1$	F^*_1	min W_1
C_2	Z_1	…	Z_n	$F_2 = \sum_1^n z$		Max	$W_2=(F^*_2-F_2)/F^*_2$	F^*_2	min W_2
C_3	U_1	…	U_n	$F_3 = \sum_1^n u$	≥	m	$W_3=(F^*_3-F_3)/F^*_3$	F^*_3	min W_3
C_n	V_1	…	V_n	$F_n = \sum_1^n v$		free	$W_n=(F^*_n-F_n)/F^*_n$	F^*_n	min W_n
Between variables									
$A_1+A_2+A_3+A_n$	$X_{1(0;1)}$ …	…	Σ		≥	1			

Table 4: Object Function (OF) associated to criterion

Impacts	OF
Yearly capability	Max.
Producibile electric energy	Max.
Heat	Max.
Other marketable products	Max.
CO	Min.
CO_2	Min.
Labour	Max.
Investment costs	Min.
Operating costs	Min.
Revenues	Max.
NPV	Max.
IRR	Max.

dependence (Table 2) and impact constraints that have to be respected (C_j in Table 2): in the model, the unique constraint added in this phase concerns the waste amount that have to be necessarily treated by the plants (T in Table 2). Waste demand is defined *a priori* considering the 50% of the yearly special waste production in Campania Region[8].

At this point it could be pursued a specific objective to be maximize or minimize, considering other objectives such as targets exogenously defined, whose level of achievement, minimum or maximum, must be respected.

The model is based on the maximization of aggregated Net Present Value ("C_2" in Table 3), as objective function. Once it has been calculated the ideal vector and chosen the objective function to be minimized or maximized, constraints ($C_1,\ldots,C_n$ in Table 3), regarding, in this specific case, waste flows entering the treatment plants, air emission, priority and overall time for plants implementation, are progressively introduced. This generate several solutions or steps (Table 6), that have to be evaluated. Each step represents a combination of constraints, so that to observe singularly the deviation between the value generated by including different constraints and the correspondent ideal vector value ($W_1,\ldots, W_n$ in Table 3).

New constraints on the level of other objectives (target) are introduced, until is achieved the best compromise solution between conflicting objectives, that could consists in minimizing the deviation from ideal vector.

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[8] The amount of total special waste in Campania Region is 801.013 t/y

The solution will be acceptable when, in the decision-maker opinion, several objectives will be obtained in the right measure.

After the compromise solution has been obtained, the analysis carry on with:

- The robustness analysis, related to the variation of the demand: foretelling a consumption reduction, after optimizing the bases-scenario, the robustness analysis aim is to evaluate how impacts change when the demand changes; nowadays, the tendency is a reduction of waste production, according to the European objective called "zero waste"
- The most robust treatment plants selection, according to the demand variation

THE OPTIMIZATION MODEL OUTCOMES

Operative options, that could be included in the plan, have been described by their main multi-dimensional characteristics. The optimization model have to consider which are the objectives of decision-maker relating to each impacts set out by treatment plants: it means that each of them have to be maximized or minimized, depending of their functions. have to consider which are the objectives of decision-maker relating to each impacts set out by treatment plants: it means that each of them have to be maximized or minimized, depending of their functions. Table 4 shows the objective function associated with each impacts.

As we explained above, the first step of the procedure consists in the determination of the ideal vector, in order to obtain individually for each impact the maximum or the minim value, depending on his objective function. The model is based on the maximization of aggregated Net Present Value as objective function. Once it has been calculated the ideal vector and the maximization of the aggregated Net Present Value, it is easy to observe that two objectives are, in terms of realization, far from the ideal vector (Tabel 5). Then we need to achieve a compromise solution not far from the ideal one, so that to achieve an acceptable value of NPV, maximizing the energy production and minimizing air emission jointly (Table 5).

Table 6 shows that, after calculating different steps, introducing progressively several constraints, (that ones in bold) on the level of achievement of several objectives, the best compromise solution is obtained at the 8th step: even if the net present value is lower than other solution, energy production and atmospheric emission are balanced.

Table 7 explains for each impact the deviation from the ideal vector. Maximizing the aggregated NPV, for instance, the realization of other impacts is far from the correspondent value of the ideal vector, mainly in term of minimizing air emissions. So the procedure is based on the introduction on constraints, step by step, that allows us to determine a compromise

Table 5: Aggregated impacts obtained by optimizing one objective individually

Impacts	Unit of measure	Max. EE	Max. Heat	Min. CO	…Max. NPV	Ideal vector
Yearly capability	T/y	387.600	387.600	355.300	387.600	400.000
Producibile electric energy	Mwht/y	1.629	1.616	766	1.601	1.629
Heat	Mwht/y	1.040	1.044	661	1.044	1.044
Other marketable products	T/y	6.412	5.459	9892	4.474	25.194
CO	T/y	363.302	359.878	190.887	360.553	190.887
CO_2	T/y	61.408	60.909	29.857	60.942	29.857
Labour	n	116	113	98	114	136
Investment costs	M€/y[9]	437	438	357	437	205
Operating costs	M€/y	28	28	21	28	14
Revenues	M€/y	207	206	121	208	208
NPV	M€/y	979	975	454	989	989

Table 6: Million of euro per year

Impacts	Max. NPV	Step 1	Step 2	Step 3	Step…	Step 8
Yearly capability	387.600	387.600	371.450	355.300	...	355.300
Producibile electric energy	1.601	1.297	952	766	...	1.139
Heat	1.044	928	748	660	...	817
Other marketable products	4.474	9.561	8.414	9.892	...	7.688
CO	360.553	343.039	221.110	190.886	...	248.390
CO_2	60.942	58.059	34.973	29.857	...	39.588
Labour	114	100	97	98	...	96
Investment costs	437	379	376	357	...	382
Operating costs	28	23	21	21	...	21
Revenues	208	189	141	120	...	158
NPV	989	928	593	454	...	708
IRR	4	2	1	1	...	1

Table 7: Deviation from the ideal vector of referende

Impact	Ideal vector	Max NPV(%)	step 1 (%)	step 2 (%)	step…	step 8 (%)
Yearly capability	400.000	-3	-3	-7	=≤=	-11
Producibile electric energy	1.628	-2	-20	-42	=≤=	-30
Heat	1.044	0	-11	-28	=≤=	-22
Other marketable products	25.194	-82	-62	-67	=≤=	-69
CO	190.886	-89	-80	-16	=≤=	-30
CO2	29.857	-104	-94	-17	=≤=	-33
Labour	136	-16	-26	-29	=≤=	-29
Investment costs	205	-113	-85	-83	=≤=	-86
Operating costs	14	-93	-62	-45	=≤=	-51
Revenues	208	0	-9	-32	=≤=	-24
NPV	989	0	-6	-40	=≤=	-28

Table 8: Constraints and compromise solution

Impacts	U. of M.	Solution N.8	Sign	Constraints
Yearly capability	T/y	355.300	=<=	400.000
Producibile electric energy	GWh/y	1.140	=>=	1000
Heat	GWh/y	817	=>=	500
Other marketable products	T/y	7.688		free
CO	T/y	248.390	=<=	250.000
CO_2	T/y	39.589	=<=	40.000
Labour	n.	96		free
Investment costs	M€	383		free
Operating costs	M€	22		free
Revenues	M€	158		free
NPV	M€	708		free
IRR	%	2		free

solution: the ones that is able to achieve an acceptable level of each impacts, considering what the decision maker intends to obtain.

Finally, Table 8 shows the constraints introduced to find the compromise solution. In this way the model has to selects treatment plants with some specific characteristics: they have to treat no more than 400.000 T/y of waste; to produce more than 1.000 GWH/y of electric energy and more of 500 GWH/y of heat; to let out less than 250.000 T/y of CO and 40.000 T/y of CO_2.

RESULTS

The model selects several treatment plants treating: urban waste (big plant); plastic (big plant); CDR (medium plant); urban waste plus tyre (medium plant); urban waste plus plastic (medium plant); urban waste plus solvents (medium plant).

The robustness analysis main aim is to understand if the selected plants could be cost-effective, after a variation demand. Two scenarios have been determined: the low one and the high one, with a percentage of 40% demand reduction and increase. The analysis outcomes show that treatment facilities which treats plastics and solvents are cost-effective, so that private company could manage them and take advantage from it, in term of large profits.

DISCUSSION

Over years, several authors have approached waste problems, suggesting specific techniques for support decisions at various stages of decision making.

Multi-criteria analysis is a tool particularly suitable for support complex decision; they are applied in cases dealing multidimensional problems typically characterized by interventions pursuing strongly inhomogeneous objectives expressed in different units of measures and subject to constraints of various kinds, in which are involved subjects and persons with a different weight in decision-making (Rostirolla, 1998).

In order to select among different alternative proposals for waste management system Hokkanen Salminem (1997) have proposed the application of Electre III, by which it is asked to the decision makers to assign weights to criteria, describing the alternatives. Costi *et al.* (2004), Minciardi *et al.* (2008) have formulated a non-linear mathematical programming problem using whole numbers so to solve problems of equipment selection, using the method of "reference point" that consist in asking to the decision makers to express their preferences.

Haastrup *et al.* (1998) have used, instead, hierarchical analysis to carry out the assessment of collection systems and the identification of areas suitable for locating

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[9] Million of euro per year

treatment plants and waste disposal. Results are the ranking of alternatives and the indications of the distance of the positions of the various interest groups involved.

The large number of multicriteria techniques involves considerations with respect to their choice application to the case of waste management. It means that even if, generally speaking, multi-criteria analysis is more suitable than others (e.g., compared to the cost benefit analysis) in addressing multidimensional nature of complex problems, however, you must choose among many techniques, those possible to better interpret the problem and overcome specifics drawbacks of other techniques. Considering the applications submitted, the drawbacks are: the ambiguity caused by the wrongful definition of the scores; the fact, that is not always preferable, to achieve a sort of alternative judged a priori all technically eligible (Electre), instead to chose a best solution; the decision makers involving in technical phases of formulation of models for the selection and/or evaluation of alternatives; the need to compare necessarily options among themselves, leading to questionable comparisons due to lack of reliable data (hierarchical analysis).

Shmeleva and Powell (2006), Erkut *et al.* (2008) have dealt problems regarding the location of treatment waste plants by using linear programming techniques in mixed-integer numbers. In the study we employ, instead, a multiobjective linear programming technique using discrete variables to solve a problem of choice among alternative treatments plants. This technique allows to overcome methodological problems of others previously analyzed. The main aim of this study was to demonstrate how multicriteria analysis could be helpful in taking complex decisions, like those concerning waste management. Given certain hypothesis, the mathematical optimisation problem, applied to a hypothetic case study, is a helpful decision support instrument and allows to choose among a set of treatment plants in order to build a platform.

The main aim was to present the structure and the application of a model designed to help decision makers in determining integrated plans; moreover considering the circumstance that in the model data were realistic, but not verified this work has been determined mostly to show a methodology by which to deal with complex problem. Given the cost-effectiveness of treatment plants and information obtained by the optimisation model, in our opinion, public authority could be able to formulate an invitation to tender, in order to favour competition for the market in waste sector.

Therefore, it could be helpful to carry out a differentiation between public and private role: public authorities could undertake different actions, consisting, for instance, in choosing the platform localization; buying the area; reclaiming the area; building up the plants; formulating an invitation to tender. Private persons, after observing economic outcomes shown by the model, could manage treatment plants paying a fee to public authority, so that to contribute to cover the costs, supported by public authorities.

The application of this methodology allows to determine the potential needs for public founds, in order to ensure the financial equilibrium for those has to build up and manage treatment plants. Further application might consist in applying the same procedure for the entire waste management cycle, from collection to treatment.

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